Crack Initiation and Growth in Rigid Polymeric Closed-Cell Foam Cryogenic Applications

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Outline

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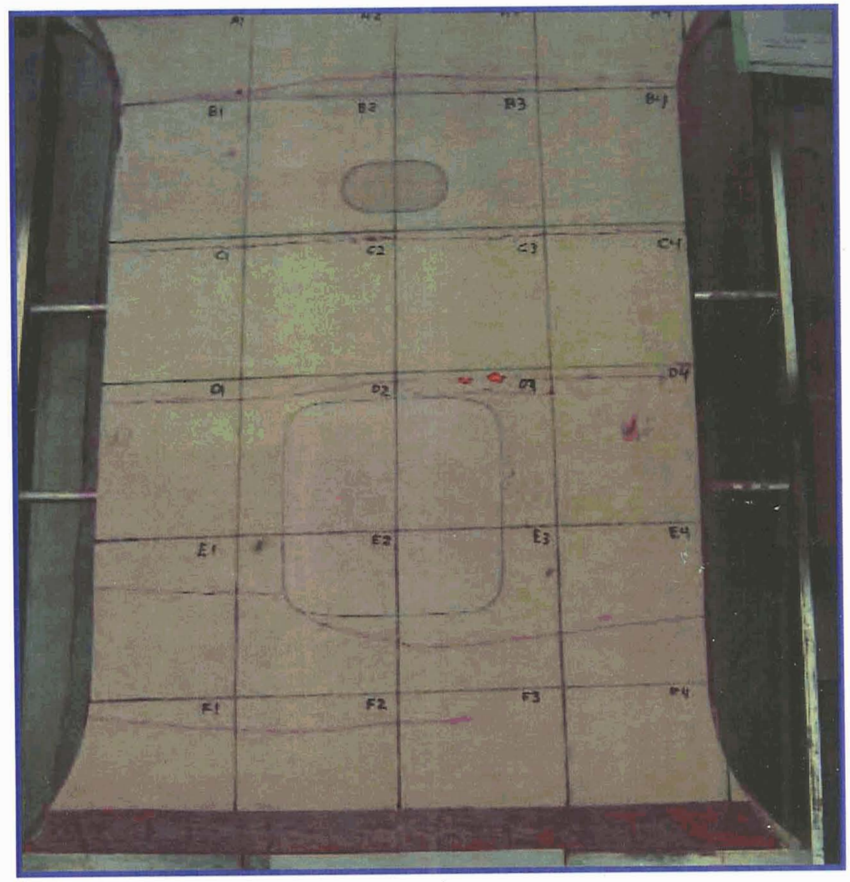
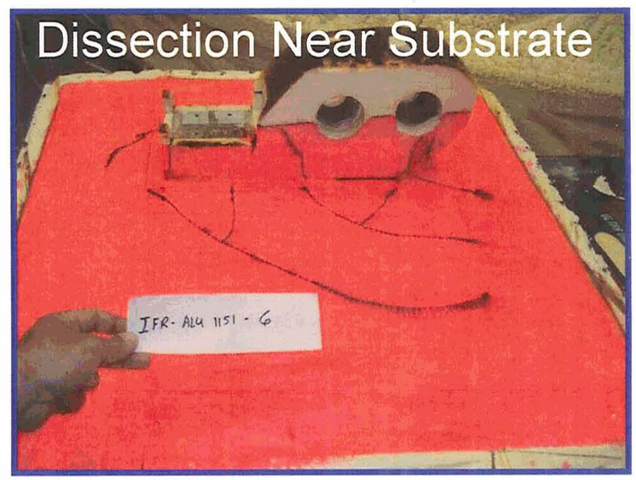


Cracking Seen in Cryogenic Tensile Test

Introduction

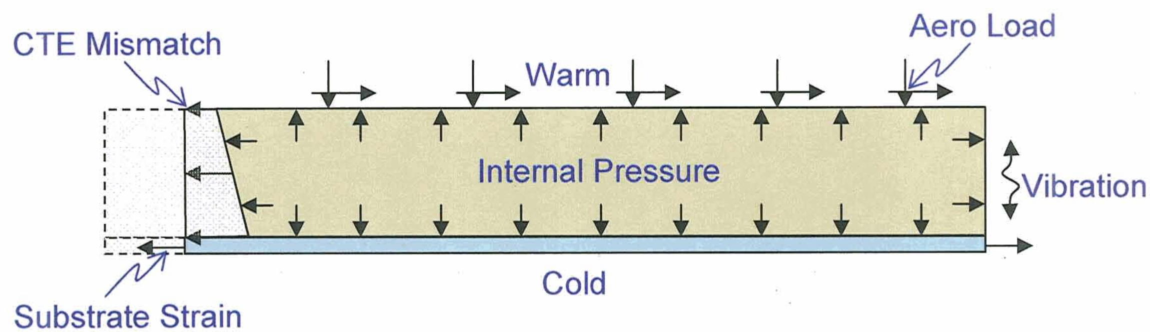
- Foam used to insulate cryogenic tanks experiences a significant amount of stress due to a CTE mismatch with the substrate and tank pressurization
- Additional stress risers can cause cracks to form
  - Additional local loading, geometric discontinuities, or regions of thick foam
- Cracks become potential sites for a substrate delamination to occur
- Cracks are also potential paths and volumes to ingest liquid air
- Understanding when and how cracks form can help to eliminate unnecessary cracking through careful design.



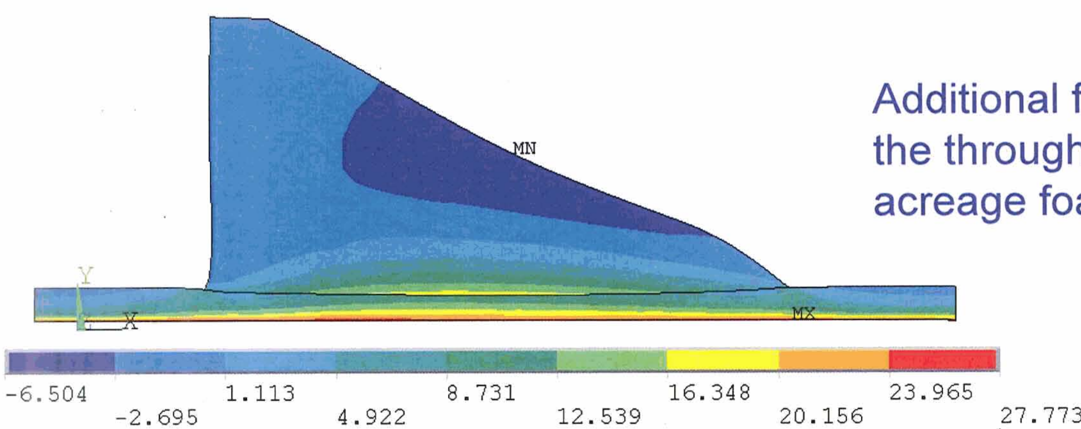
Ice-frost ramp testing
Cryogenic substrate, external vacuum and heating

Introduction

- External Tank foam experiences multiple loads during pre-launch and ascent



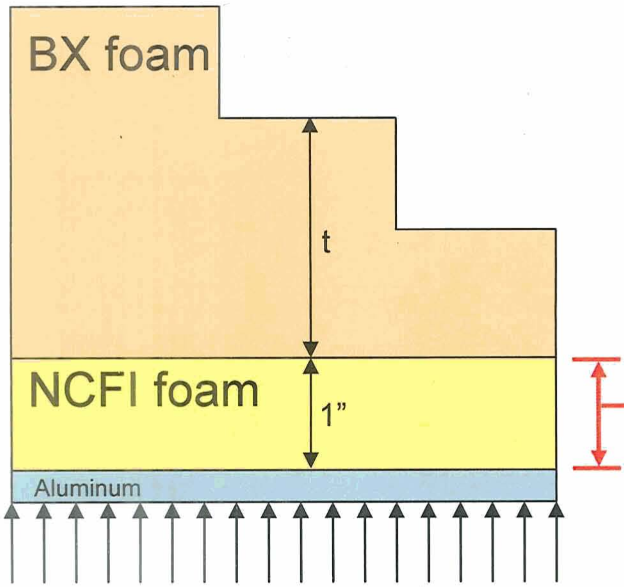
- The primary loads are the CTE mismatch with the aluminum, the tank substrate pressurization strain, and the internal pressure/external vacuum
- The peak stresses occur at the substrate



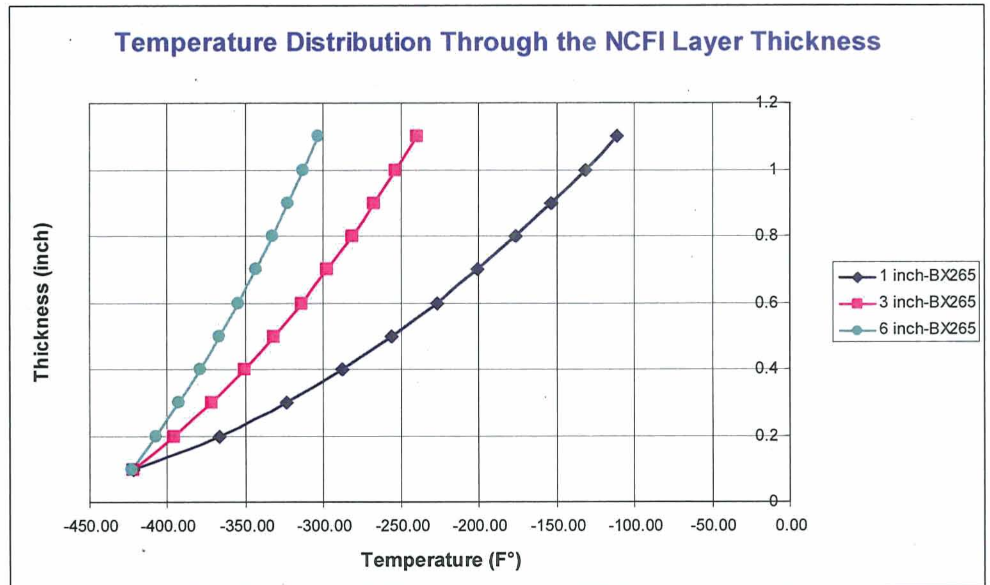
1st Principal Stress Profile (psi)

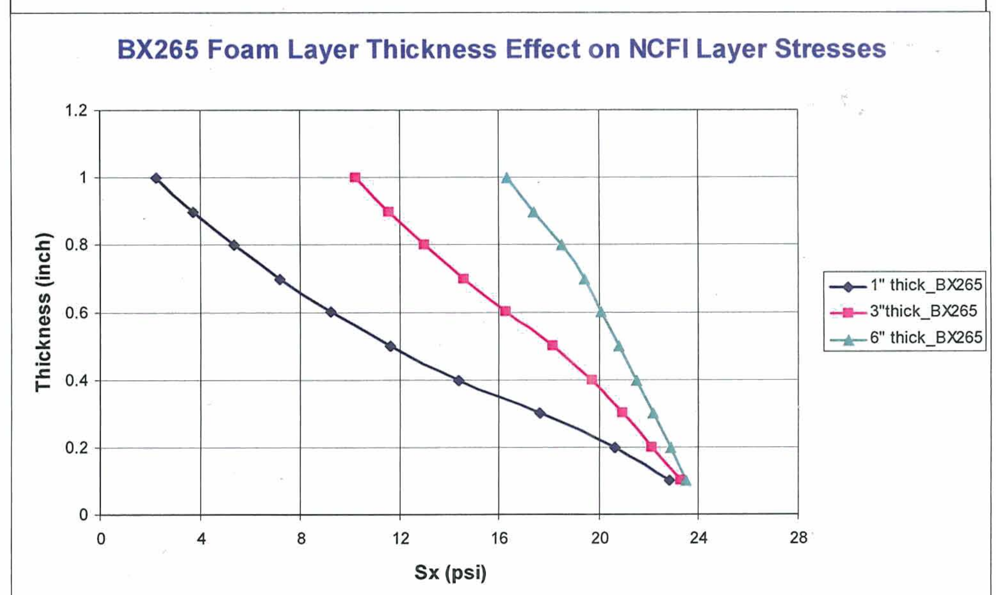
Additional foam-over-foam increases the through thickness stress in the acreage foam underneath

Stress and Temperature Profiles



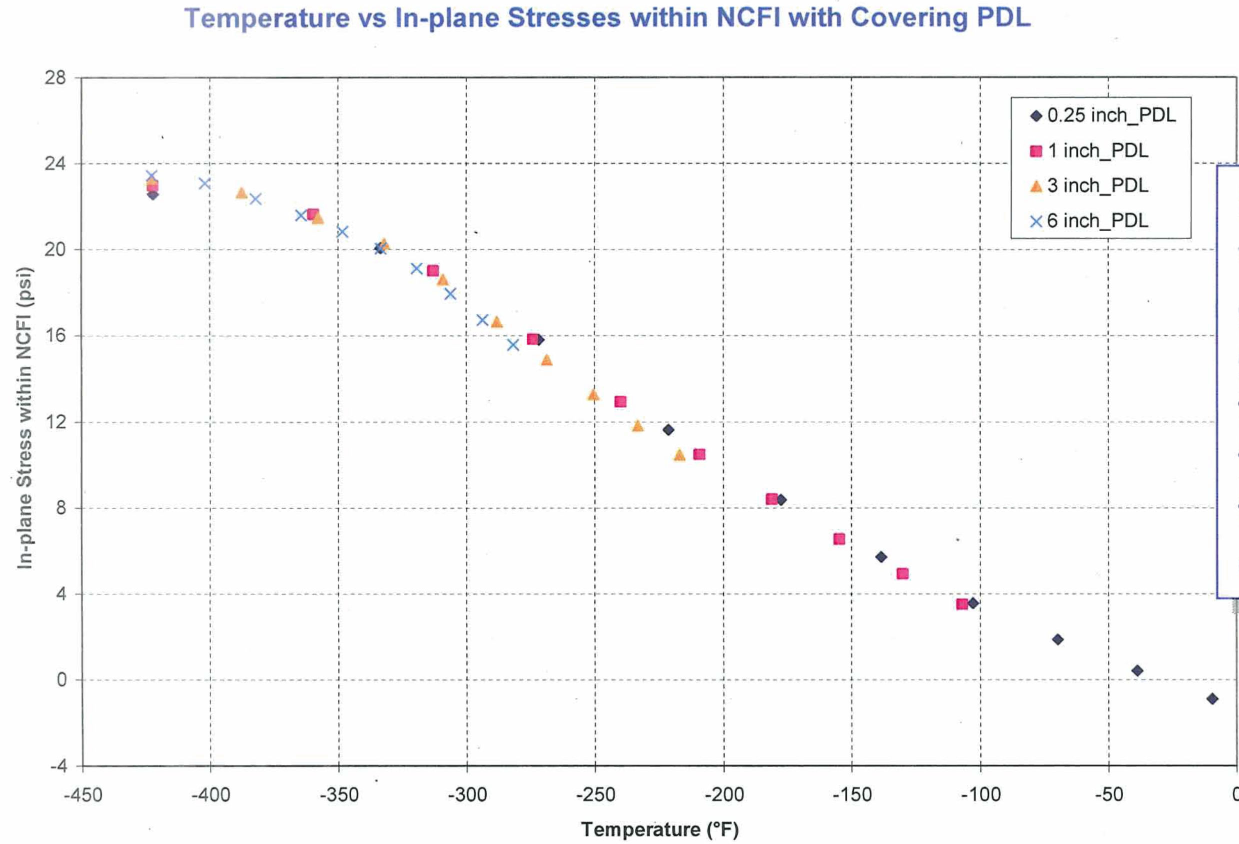
LH2 Cooling



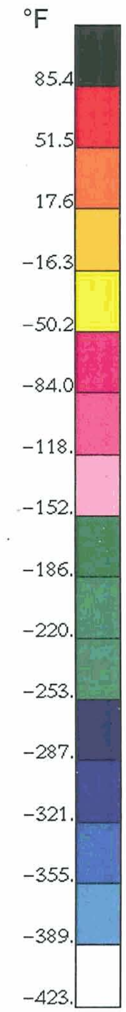


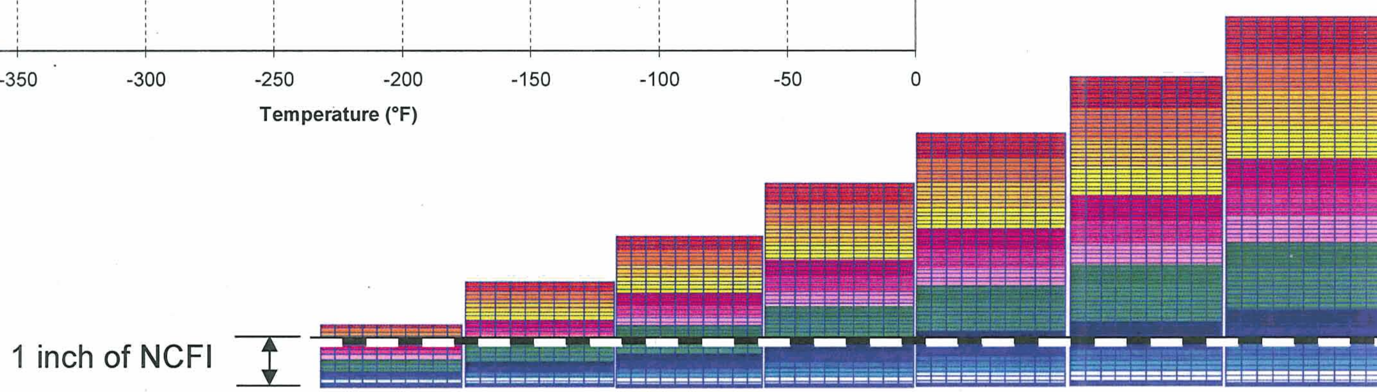
Height of BX or PDL foam over NCFI foam controls the temperature in the NCFI layer, which in turn controls the stress due to thermal mismatch between aluminum substrate and foam.

Stress-Temperature Relationship



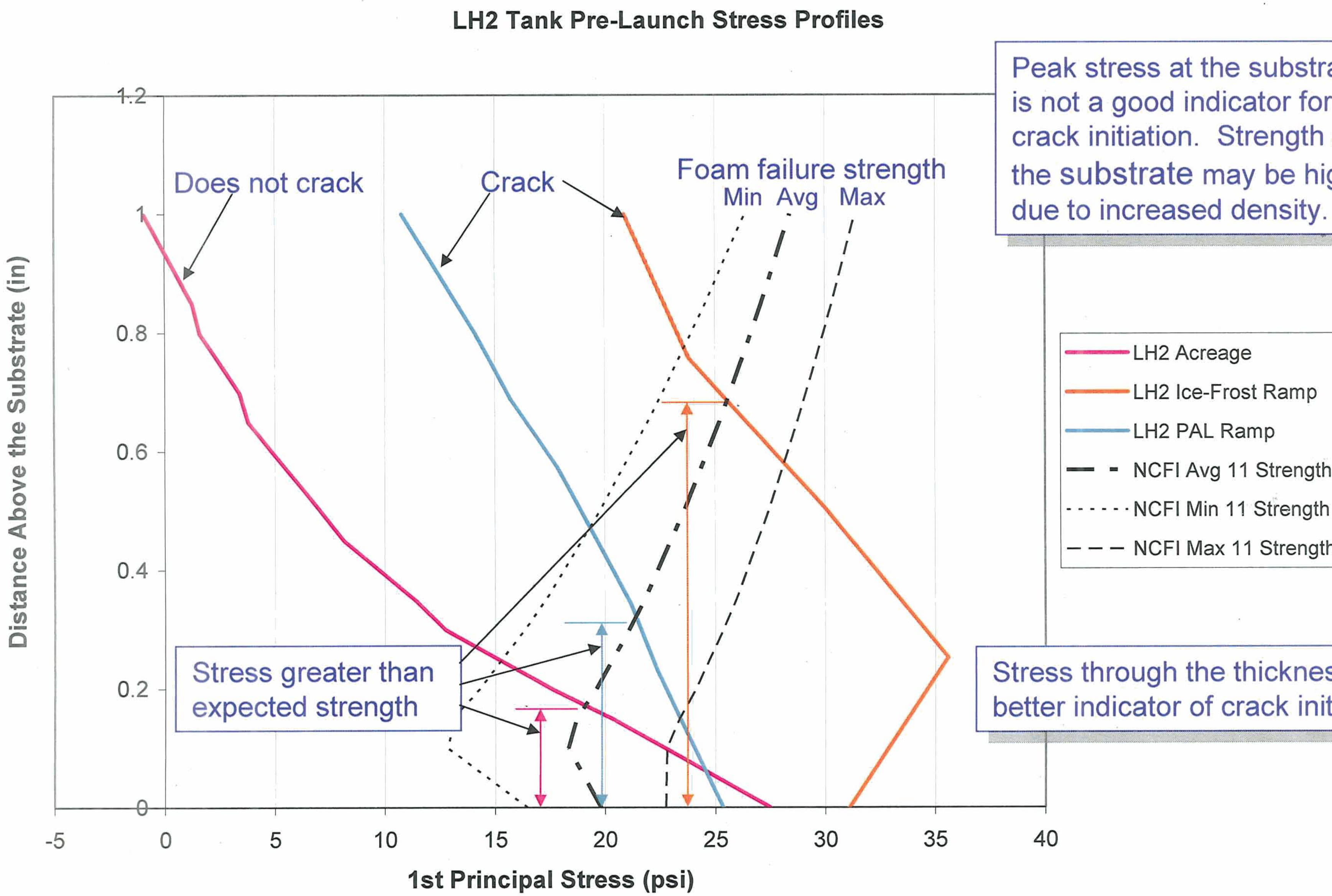
Stress profiles for various temperature gradients collapse to a general stress-temperature correlation for locations away from free edges or discontinuities.





<u>Thermal Analysis of BX265 Over NCFI Results (Full Temperature Range @ t=6")</u>

Crack Initiation



Peak stress at the substrate is not a good indicator for crack initiation. Strength at the substrate may be higher due to increased density.

Stress through the thickness is a better indicator of crack initiation.

Foam Fracture

Foam Failure

- Rigid polyurethane foams fail in a brittle fashion under tensile loads, particularly at cold temperatures
- Fracture mechanics is used to predict the crack growth of pre-existing cracks
- LEFM successfully correlated with critical defect testing results
    - Adequately predicted when a circular or slotted flaw would fail under a external vacuum and aero-heating load as a function of flaw diameter and depth

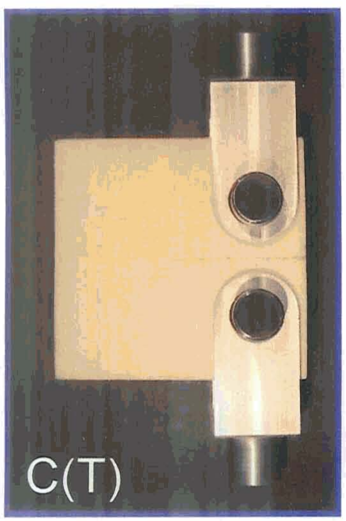
Analytical Assumptions

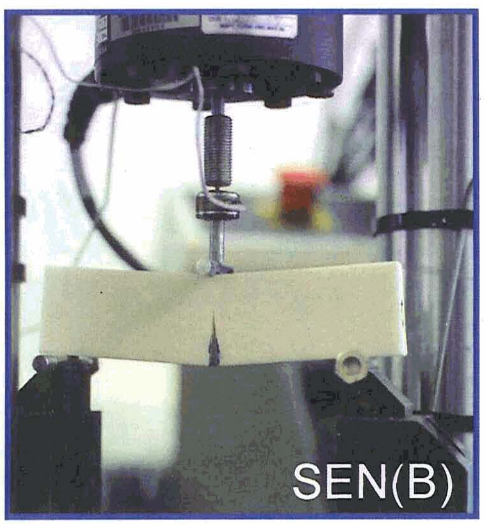
- Transversely isotropic properties used to model TPS
- Linear elastic fracture parameter K_I used to predict onset of cracking
- Stress intensity calculated using crack face opening displacements assuming isotropic properties

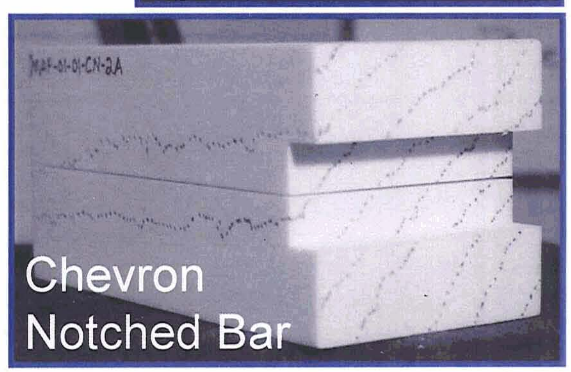
Linear Elastic Fracture Mechanics

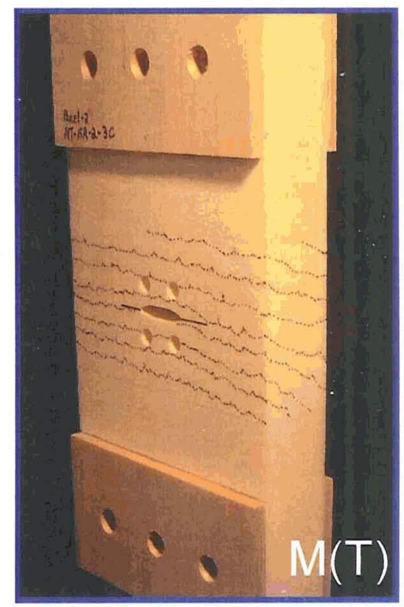
Experimental Substantiation of LEFM as an Engineering Tool

- Correlation of failure
  - Stress intensity factor, K, predicts failure load accurately
- Consistent measure of toughness across geometries and loading conditions
  - Toughness found to be consistent, within expected material variability, for all cracked geometries tested. Provides substantiation for use of a single parameter fracture criterion (K).
- Linear load-displacement records during test
  - Linear elasticity prevails for all standard test geometries at temperatures <= 70F.


C(T)

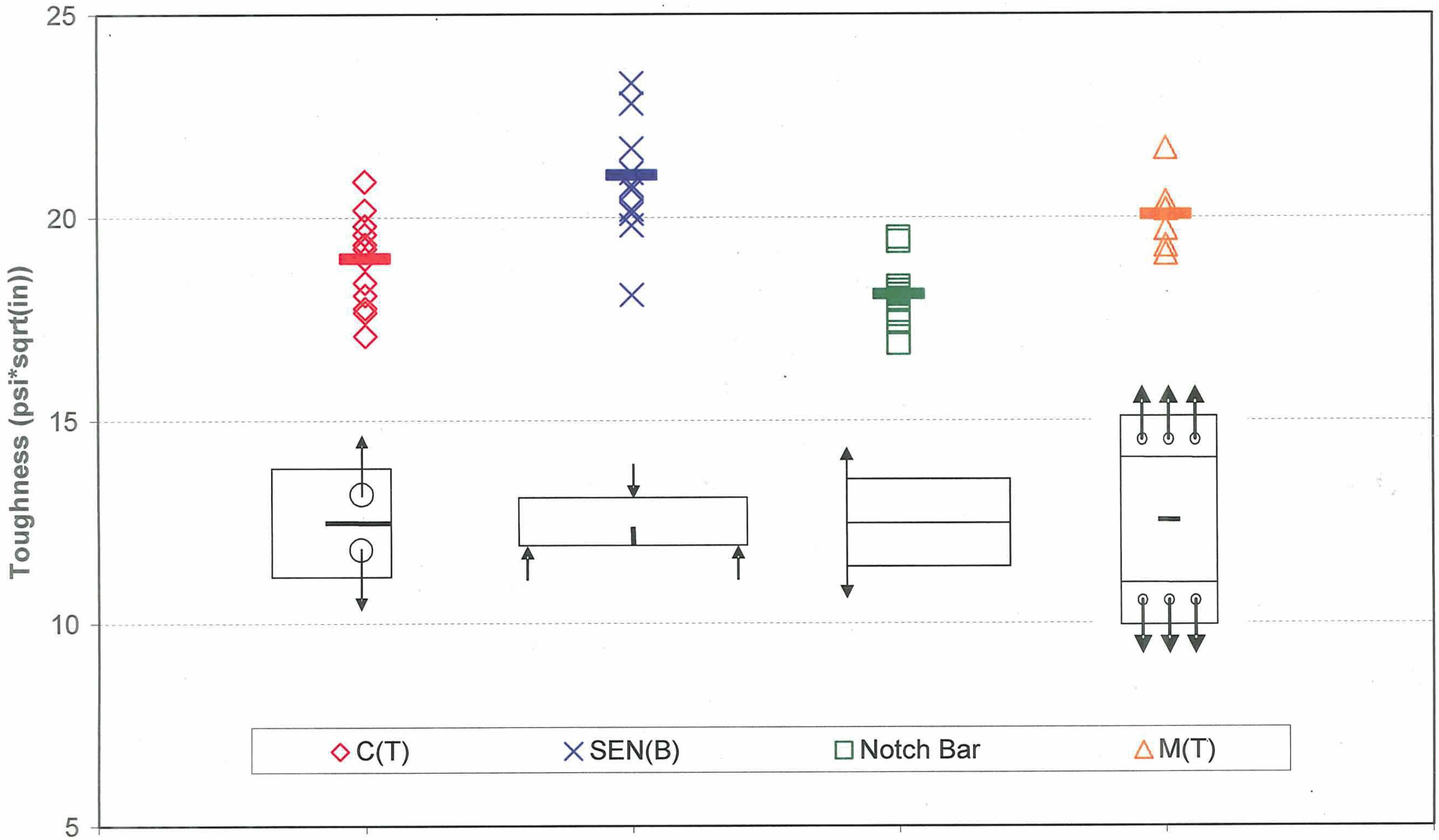

SEN(B)


Chevron Notched Bar


M(T)

Linear Elastic Fracture Mechanics

LEFM Consistency Across Geometries

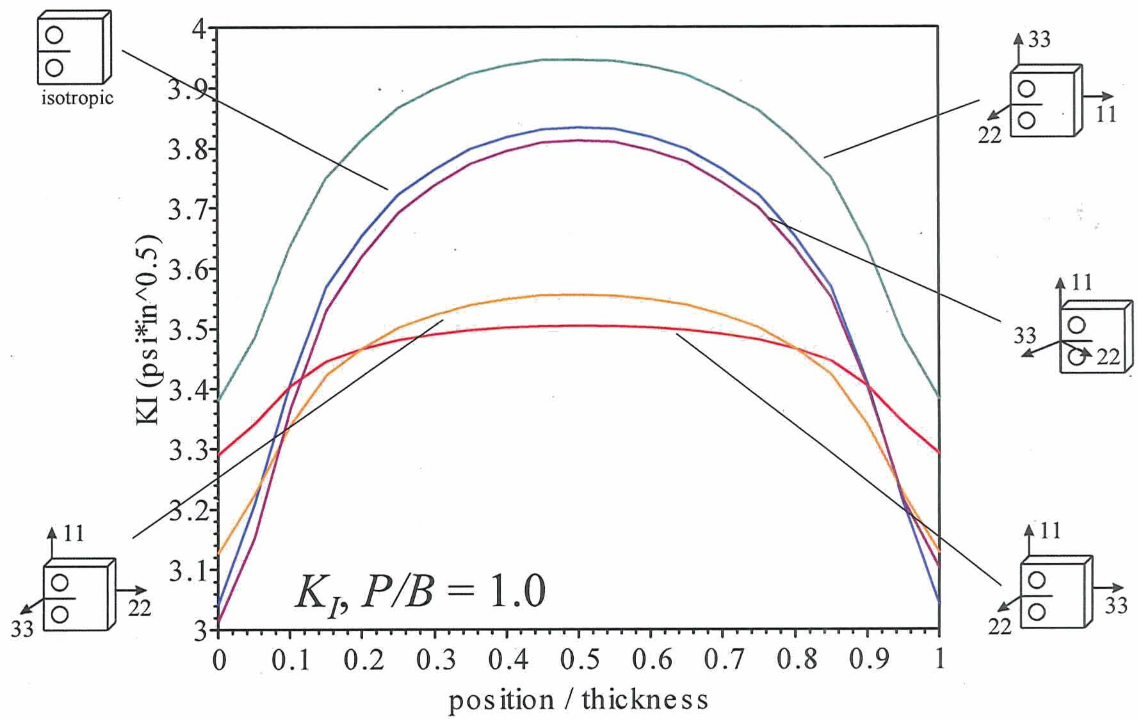


Anisotropic Effects

- Experimental substantiation tests indicate that application of the stress intensity factor using isotropic homogenous assumptions is a valid engineering approach as long as all length scales for the cracked body (crack length, ligament, thickness, etc.) are very large compared to the cellular microstructure.
- The effects of anisotropic material behavior on the K-field and mixed-mode contributions have been modestly investigated and found to introduce error on the order of 10%.

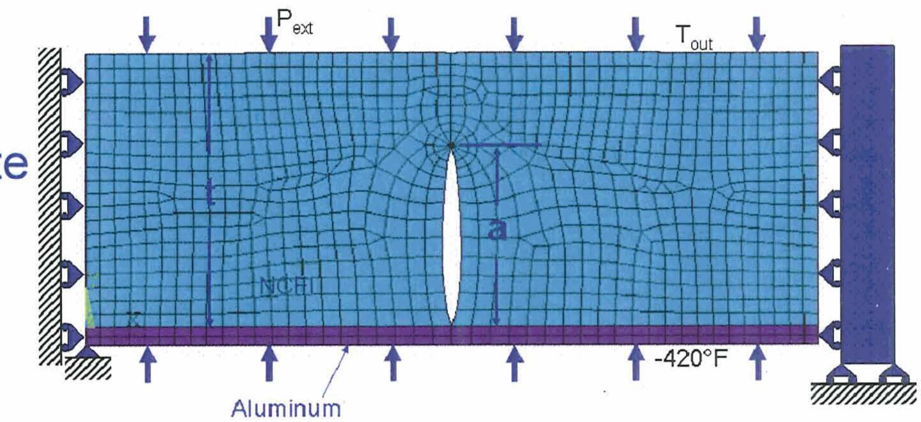
Assessment performed by
Dr. Paul A. Wawrzynek and
Dr. Bruce J. Carter

Fracture Analysis Consultants, Inc.



Flat Panel Crack Growth Resistance

Subsurface Normal Crack Resistance Curves

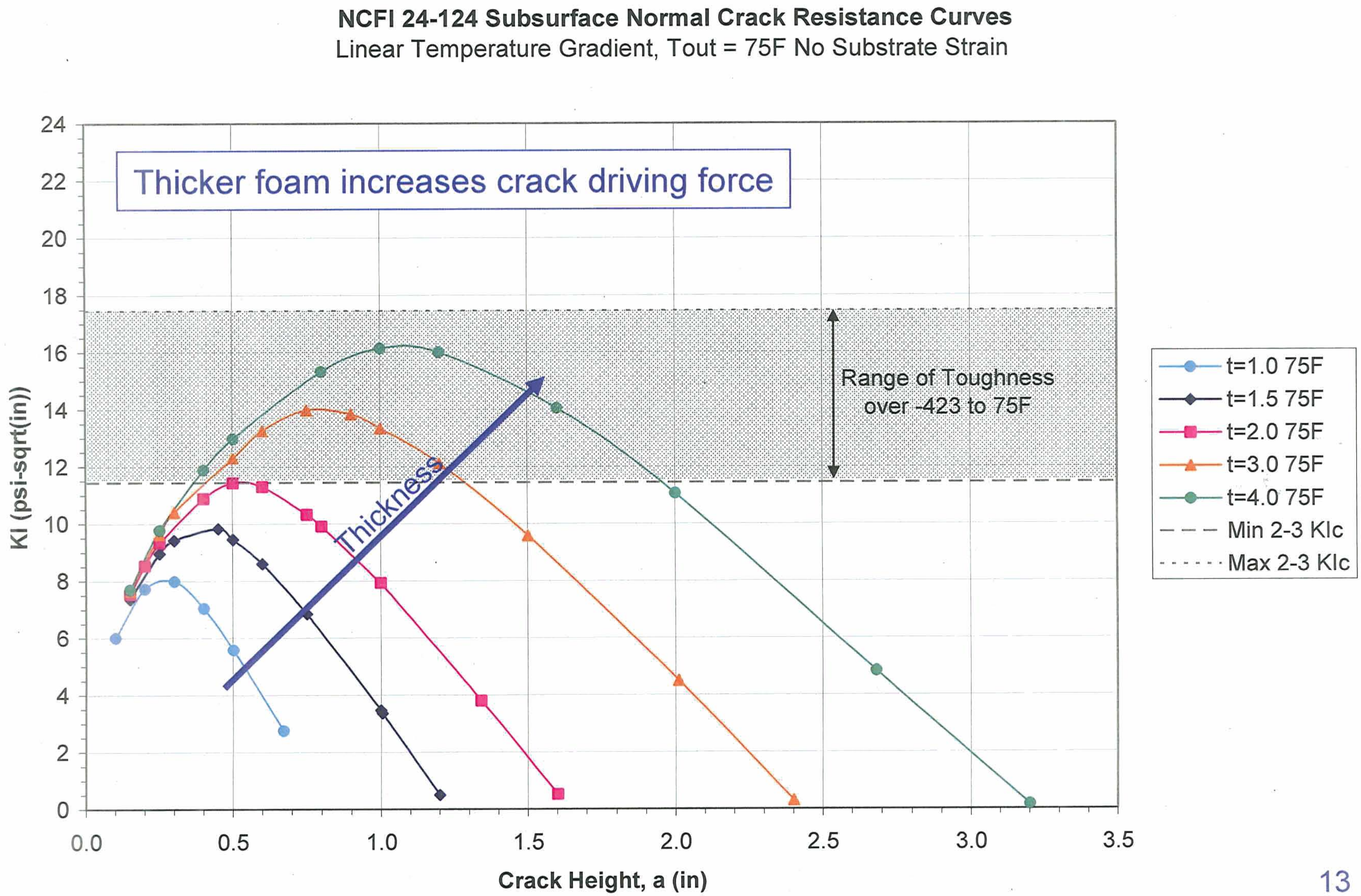


- Determined using simple 3D FE model
    - Foam on a flat 0.25" substrate
    - Through crack normal to the substrate
    - Symmetry boundary conditions simulating an infinite acreage
- Linear thermal gradient
    - -420°F at the substrate
    - 75 or 0°F at the outer surface
- Substrate uniaxial stress (60ksi) applied in some cases
- Orthotropic material properties (rise direction normal to substrate)
    - Crack in 1-3 orientation
- NCFI alone and NCFI under PDL or BX-265

- Stress intensity calculated using ANSYS *kcalc* fit to crack face opening displacement
    - Uses isotropic in-plane properties to calculate KI

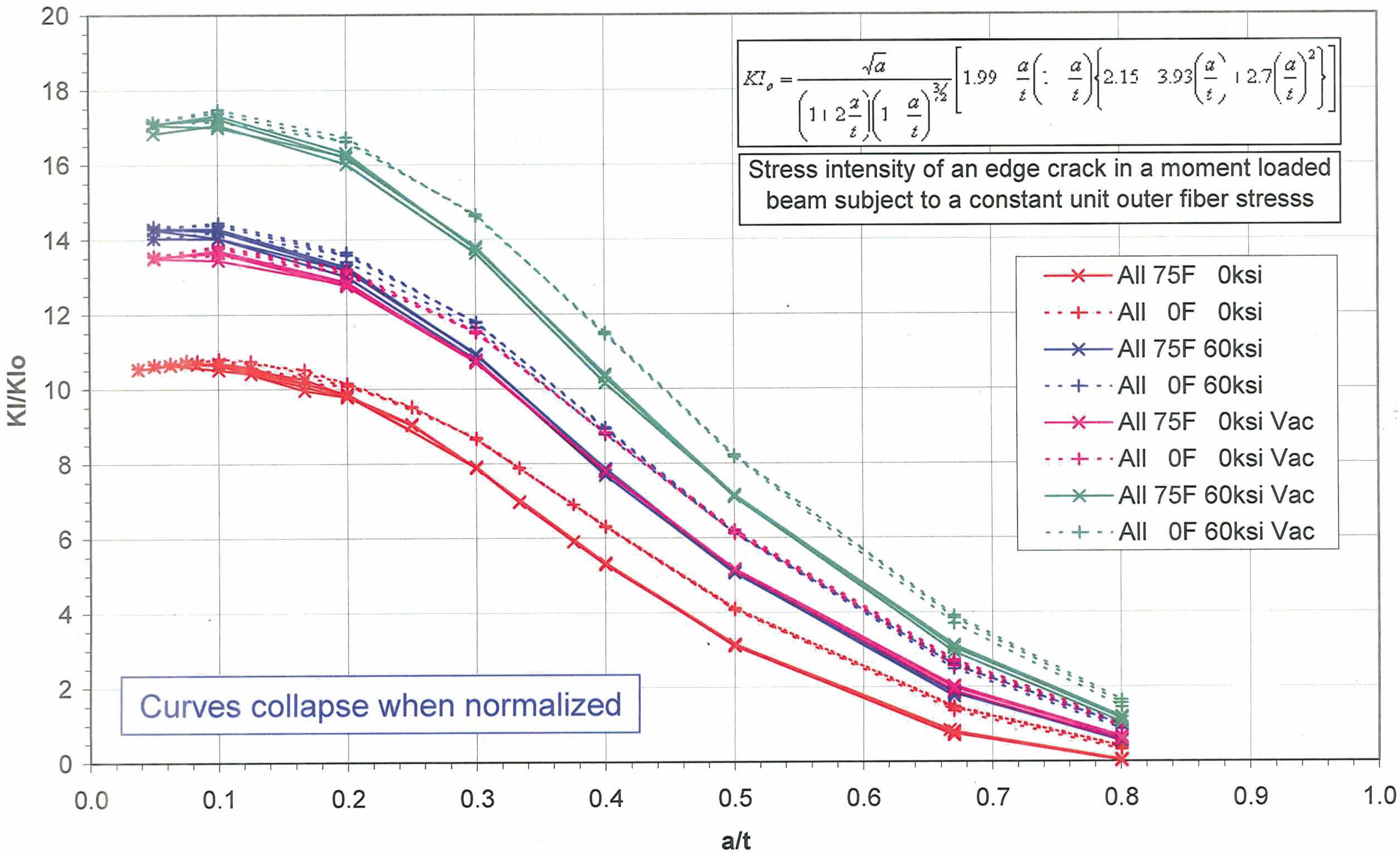
- Stress intensity compared to range of KIc in the 2-3 direction

NCFI Flat Panel R-Curves



NCFI Flat Panel R-Curves

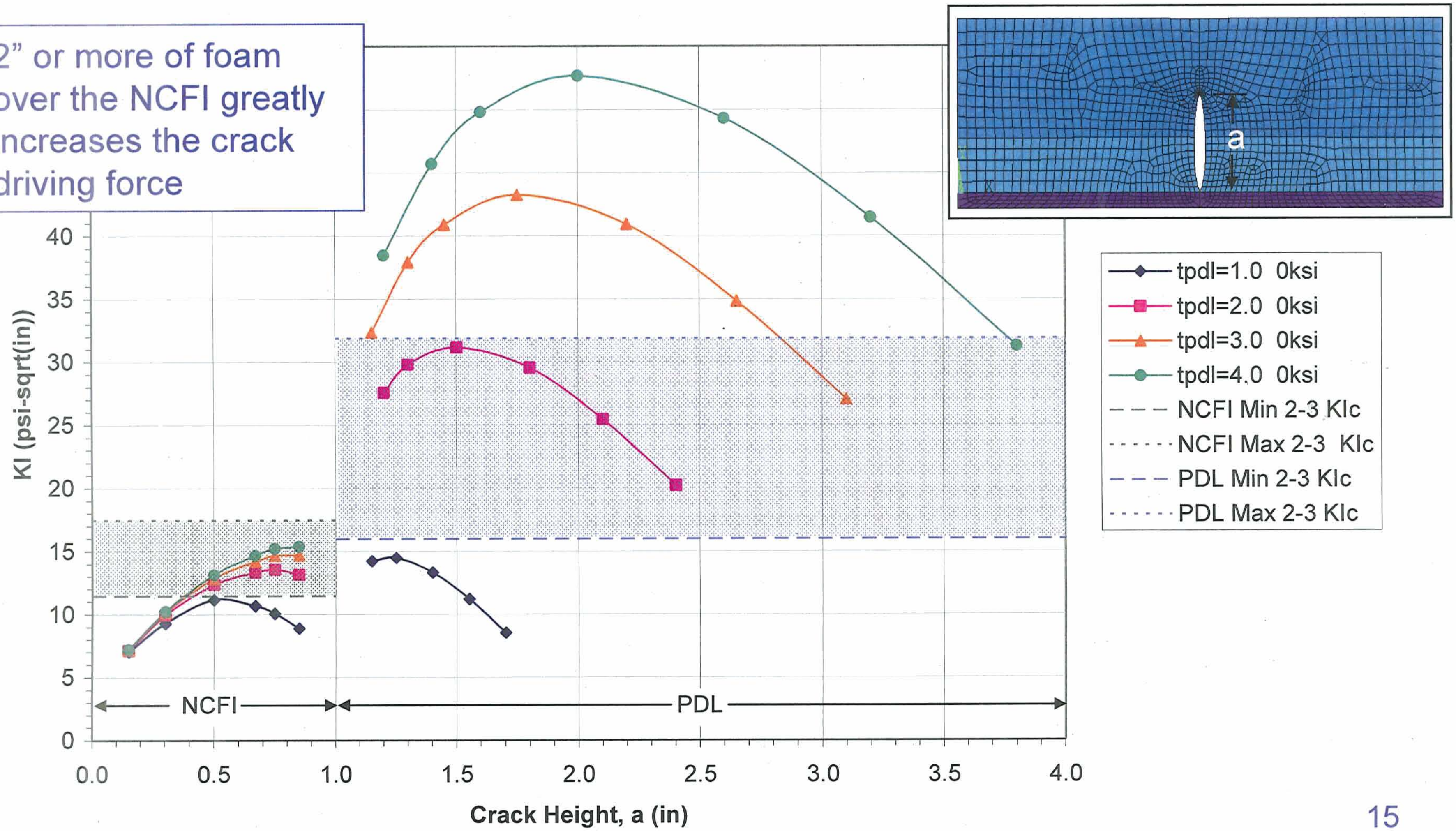
- Substrate stress and vacuum significantly increase stress intensity
- Colder outside surface temperature affects results near the surface



NCFI Under PDL R-Curve

PDL 1034 over NCFI 24-124 Subsurface Normal Crack Resistance Curves
Linear Temperature Gradient, Tout = 75F, NCFI Thickness = 1.0in

2" or more of foam over the NCFI greatly increases the crack driving force

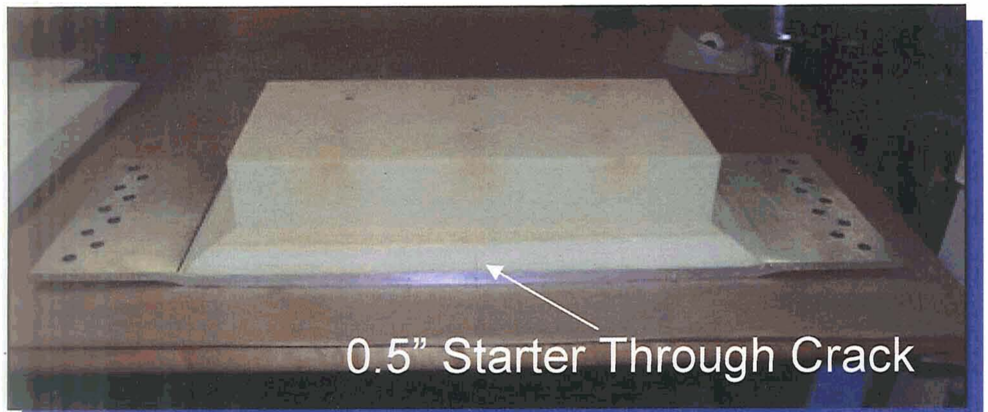


Orthogrid Tensile Test Panel

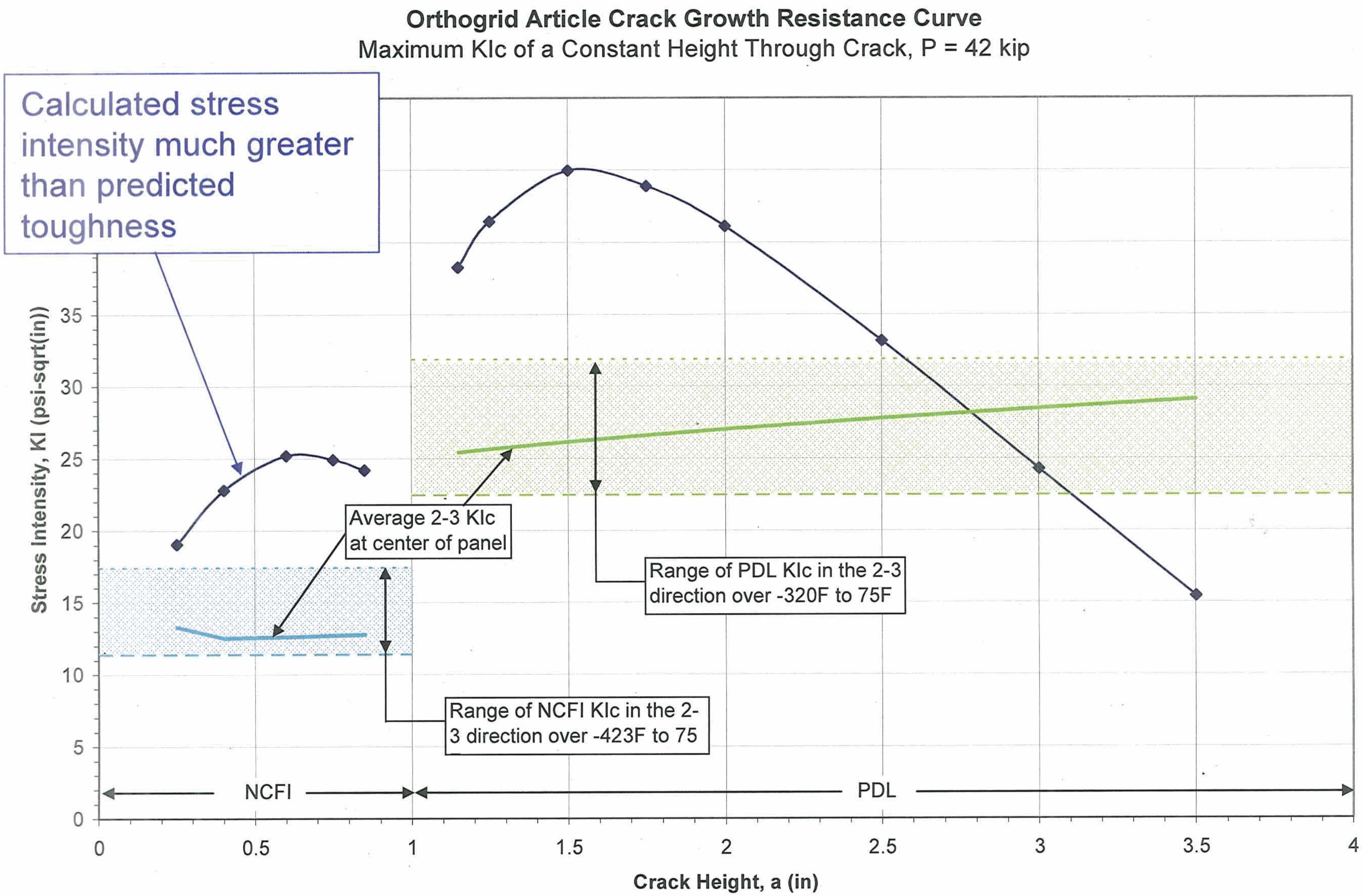
Panel Description

- 12" wide uniaxial tensile panel
- Aluminum substrate
- 1" thick NCFI under 3.3" of PDL
- Orthogrid stiffener pattern in gage section
- Includes ½" starter through crack
- Substrate is chilled with liquid helium
- Maximum load is 75,000 lb

- Two panels tested so far
  - Panel 1: Starter crack extended at 42 kip
  - Panel 2: No noticeable crack growth

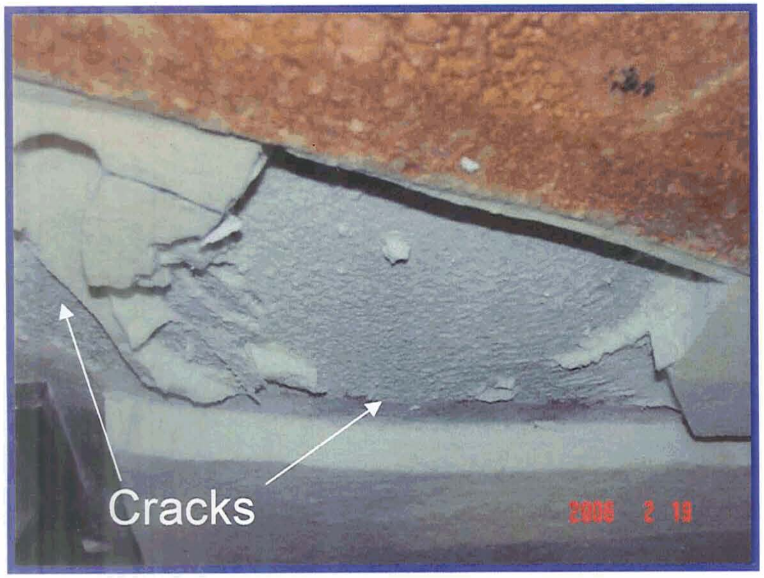


Orthogrid Tensile Test Panel R-Curve



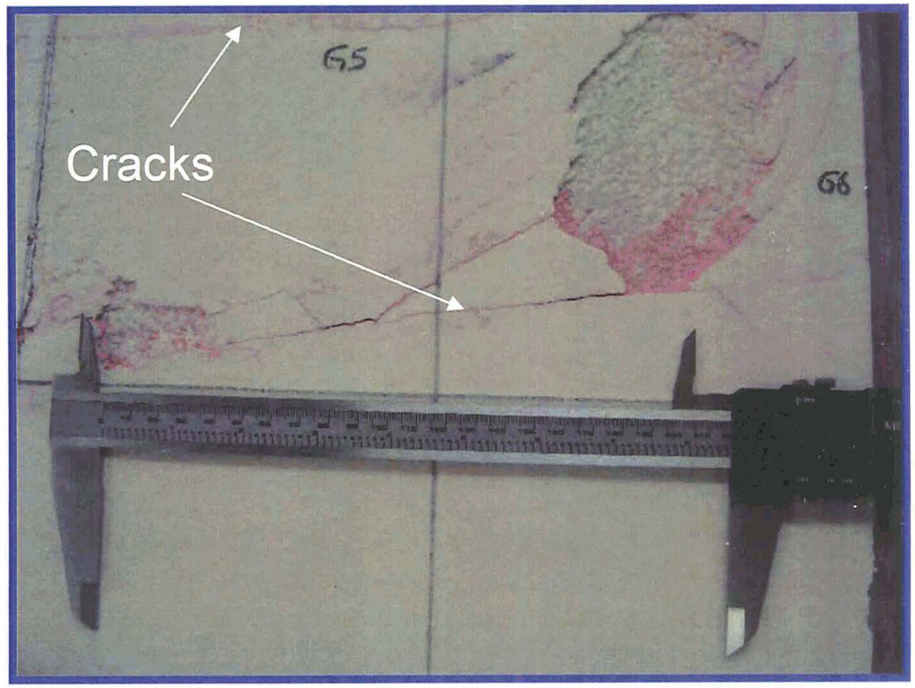
Delamination

- At sufficient load cracks will form which may initiate a delamination near the substrate
- Cracks introduce a peel and shear stress concentration
- Delaminations often occur just above the substrate near the first knitline

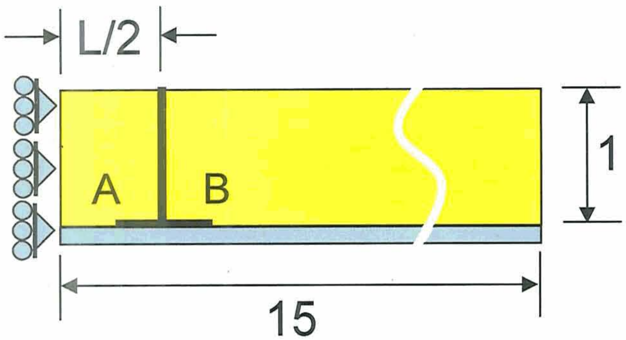


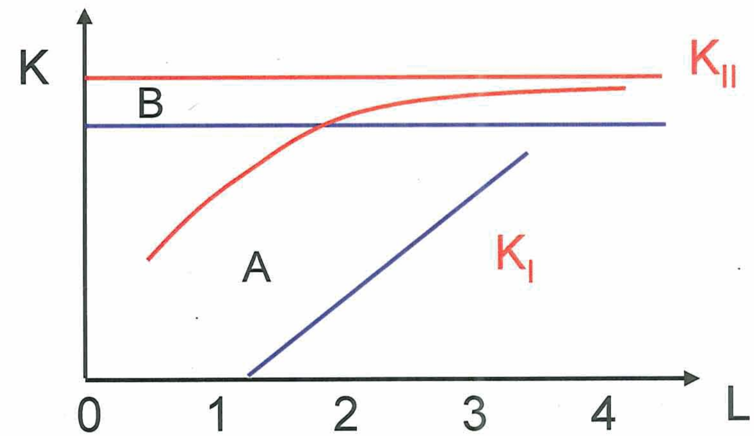
LH2 Ice-Frost Ramp

Wide Panel Test



Thermal Crack and Delamination Interaction

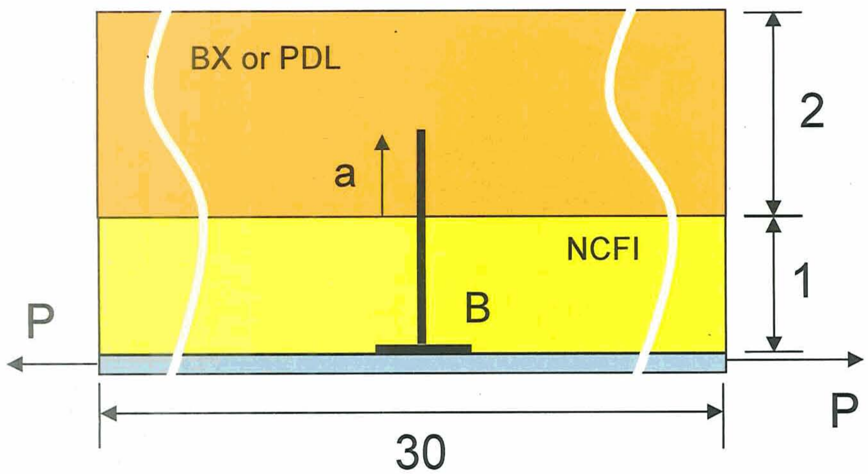




- Delamination interface cracks at A and B are 0.25 long
- Loading by uniform $\Delta T = -493F$

- ABAQUS 2D plane strain model, domain integral for K evaluation
- Parametric assessment performed, small subset shown
- Observations on thermal crack and delamination interaction effects:
    - Delamination is most commonly observed between thermal cracks
    - K_I and K_{II} driving forces are reduced if thermal cracks are within 4 to 5 inches of each other
    - Additional contributors to the mode I and II driving forces between the thermal cracks are likely required to create and propagate delamination

Delamination Crack Driving Forces



Loading: Thermal equilibrium gradient (-423F to 70F) and substrate strain

P →	0	60ksi	0	60ksi
a ↓	K_I	K_I	K_{II}	K_{II}
1	5	30	14	22
Thru			14	24
	Vertical		Delamination	

- ABAQUS 2D plane strain model
- Domain integral for K evaluation
- Large parametric assessment performed, small subset shown
- Observation on substrate strain effects:
  - Generally adds approximately 15-20% to thermal stresses
  - Influence on crack driving forces is more significant
  - Vertical (thermal) crack K_I can be strongly affected, 6x in this example
  - Interface (delamination) crack K_{II} reflects 2x factor in this example

Conclusion

- Linear elastic fracture mechanics is a good tool to describe fracture in rigid polyurethane foams
- Currently do not have a good indicator to predict crack initiation in foam on a cryogenic substrate
  - Related to peak stress and stress gradient through the thickness
- Thick foam and foam-over-foam applications have a greater crack driving force to propagate cracks toward the surface
- Orthogrid panel results show less propensity to grow a crack than predicted analytically
- Substrate strain significantly increases the delamination driving force